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THE TAURUS-LITROW DARK MANTLE, LIGHT MANTLE, CRATER CLUSTER, AND SCARP. Baerbel K. Lucchitta, U.S. Geological Survey, Flagstaff AZ 86001, USA.

The Taurus-Littrow landing site is on the floor of a grabenlike valley that is radial to the Serenitatis Basin; the valley is gently inclined to the east. It is bordered by steep-sided massifs that rise 2 km above the valley floor and form part of the Serenitatis Basin rim [1,2]. The valley floor is exceptionally dark, and in one place it is overlain by a light-colored mantle apparently derived from the massif to the south. The floor is also peppered by overlapping craters. A scarp, up on the west, transects the valley floor and enters the highlands to the north.

Before the mission, the valley floor was interpreted to be covered by a dark mantle that also covers part of the highlands along the southeastern rim of the Serenitatis Basin [3-5]. The dark unit has an albedo as low as 0.79, which is darker than the outer dark mare ring in the Serenitatis Basin [6]. The dark mantle was generally interpreted to be a young pyroclastic deposit. The reasons for the young age assignment were (1) a dearth of small craters when compared with crater densities on surrounding mare surfaces and (2) the observation that the dark mantle appears to cover young craters and the fresh-looking scarp. Postmission analysis established that the dark material in the landing area is mostly composed of old mare regolith averaging about 14 m in thickness and containing about 5% dark beads [7]. These beads are associated with orange beads in the ejecta of a small crater. The generally accepted postmission interpretation of the dark mantle is that it is a deposit of dark and orange beads erupted from fire fountains soon after the mare basalts were emplaced [7], and that the reworking of the beads into the regolith gave it the low albedo [1,2]. The presence of orange and dark layers on mare and highland material at the base of the regolith is also supported by detailed studies of the Sulpicius Gallus Formation on the west side of the Serenitatis Basin, where many outcrops give clues to the stratigraphic relations [8]. There the dark mantle covers mare and highlands with deposits on the order of 50 m thick. The reason for the paucity of small craters in the dark mantle is now attributed to the unconsolidated, friable nature of the mantle; small craters are eroded much more rapidly by mass wasting and impact gardening than in the adjacent hard-surfaced, younger lavas, which have thin regoliths [9].

The controversy concerning the light mantle mostly centers on whether it is a simple avalanche deposit or whether it was emplaced largely by impact (whereby secondary projectiles may have hit the top of the massif from which the light mantle is derived and dislodged the material). A detailed study of secondary impact craters of Tycho over the entire lunar nearside showed that Tycho secondaries have distinctive characteristics [10]: they are crater clusters with sharp, fresh-looking surface textures; the surface downrange from secondary craters displays a braided pattern with V-shaped grooves and ridges; acute angles of the Vs as well as the trend of many ridges, together with the overall cluster trend, point in the general direction of Tycho. An analysis of the light mantle, the crater cluster on top of the massif, and the crater cluster on the valley floor showed that the Tycho secondary characteristics are present. Thus, the light mantle is not a

true avalanche but an impact-propelled feature, and the crater cluster on the valley floor is composed of Tycho secondaries. The scarp on the valley floor displays the typical characteristics of a mare-type wrinkle ridge. Wrinkle ridges in the Serenitatis region were studied by several authors [11] and were generally considered to be thrust faults. A detailed study of the scarp on the valley floor and its continuation into the adjacent highlands showed that it has characteristics of high-angle normal and high-angle reverse faults [12]. It is likely that this scarp is the surface expression of minor postmare adjustments along high-angle faults that reactivated older faults bordering basin-rim massifs.

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MORPHOLOGY AND COMPOSITION OF CONDENSATES ON APOLLO 17 ORANGE AND BLACK GLASS. David S. McKay¹ and Sue J. Wentworth², ¹NASA Johnson Space Center, Houston TX 77058, USA, ²Lockheed, 2400 NASA Road 1, Houston TX 77058, USA.

Background: Lunar soil sample 74220 and core samples 74001/2 consist mainly of orange glass droplets, droplet fragments, and their crystallized equivalents. These samples are now generally accepted to be pyroclastic ejecta from early lunar volcanic eruptions [1,2]. It has been known since early examination of these samples that they contain surface coatings and material rich in volatile condensable phases, including S, Zn, F, Cl, and many volatile metals. Meyer [3] summarizes the voluminous published chemical data and calculates the volatile enrichment ratios for most of the surface condensates.

The volatiles associated with these orange and black glasses (and the Apollo 15 green glasses) may provide important clues in understanding the differentiation and volcanic history of the Moon. In addition, condensable volatiles can be mobilized and concentrated by volcanic processes.

The Problem: While considerable chemical data exist on these samples, the phases that contain the volatile species are not known; no unequivocal condensate mineral has ever been identified in these samples, with the possible exception of sodium chloride salt crystals [4]. No X-ray diffraction or electron diffraction data exist on any of these phases. More positive information on the phases or mineralogy of the condensates would lead to a better understanding of the nature of the volatile gases from which they formed and the temperature, total pressure, and gas fugacity conditions associated with the eruption. This in turn would lead to a better understanding of lunar extrusive volcanism and of the history of the magma from which the pyroclastics came.

Some basic questions still unanswered include

1. What is the composition of the gas phase of the eruption? Was the major driving gas CO-CO₂ or was it something else?
2. What is the source of the condensable volatiles found on the droplets? Are they all indigenous lunar volatiles? Are any of them,

particularly the siderophiles, from meteorites? Are they from primitive undifferentiated regions at depth?

3. What were the conditions of the eruption? At what point in the eruption were volatiles condensed on droplet surfaces? Were volatiles still mobile after the pyroclastics were deposited and were some of them condensed at that time? Were conditions present that might lead to volatile concentrations in some part of the deposit? Is it likely that such concentrations exist and can they be located?

Approach: We have reviewed many of our existing photomicrographs and energy dispersive analysis (EDXA) of grain surfaces and have reexamined some of our older SEM mounts using an improved EDXA system capable of light-element detection and analysis (oxygen, nitrogen, and carbon).

Results: (1) *Micromounds.* The 74001/2 glasses have micromound coatings (Fig. 1), which were first described and named by Heiken et al. [1] and appear to be characteristic of other lunar volcanic glasses such as the Apollo 15 green glasses. Individual micromounds range in size from ~20–300 Å (e.g., [4]). The micromound coatings commonly contain scrapes and gouges that suggest that the glasses were abraded while the micromound coatings were still soft, i.e., during fire fountaining. The sizes and densities of micromounds vary from glass to glass. In some cases, they form relatively large masses of micromounds (Fig. 2). (2) *Shrinkage cracks and vesicles.* Very dense continuous coatings have also been found; some of the continuous coatings contain cracks (Fig. 3) and vesicles that may have resulted from shrinkage during cooling, from desiccation, or by evolution of a volatile species [4]. In addition to micromounds, the glass surfaces also contained volatile-rich grains, such as NaCl phases and sulfur-rich forms. Some sulfur peaks were large, suggesting that elemental sulfur might even be present. The volatile-rich phases were found as small euhedral crystals, such as the NaCl in Fig. 4, and as more massive forms, such as the round NaCl(?) puddles in Fig. 5a.

Secular changes. Our current studies of the surface features on the 74002 glasses show quite clearly that the volatile species have been affected by the storage of the samples at ambient conditions since 1978. Figures 5a and 6a are SEM micrographs obtained in 1978;

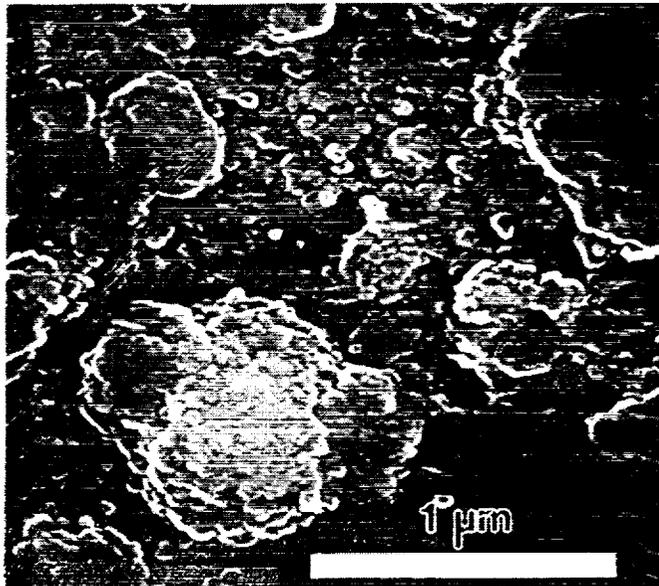


Fig. 2.

the surface deposits identified at that time were Na and Cl in both views (the round masses in Fig. 5a and the 2- μ m-size flat, angular grain at the center of Fig. 6a). Figures 5b and 6b are SEM images of the same two areas obtained in 1992, and they demonstrate that both surfaces have undergone significant changes. In Fig. 5b, the round NaCl masses have disappeared and although the rest of that surface is much like it was, there is some indication that the bumpy micromound surface has been somewhat subdued and otherwise changed. The surface of Fig. 6b shows a much more drastic change from the earlier surface of Fig. 6a: It is now covered by a dark deposit consisting of Na or Zn (the two peaks cannot be readily distinguished) and S. The



Fig. 1.

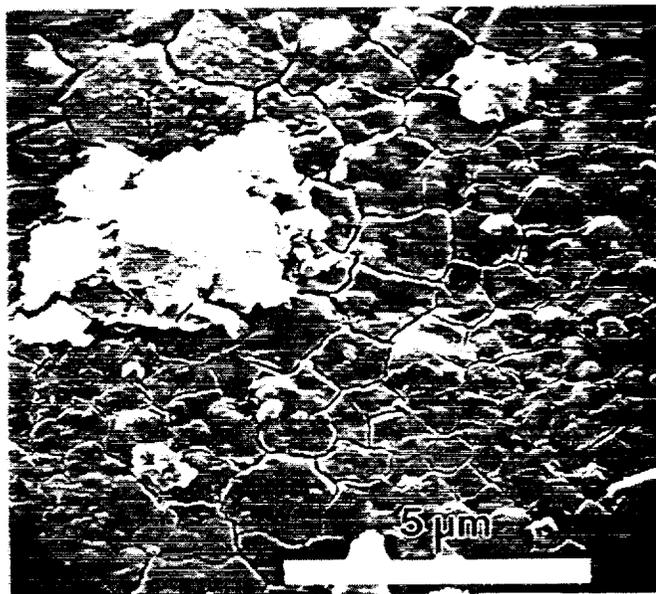


Fig. 3.



Fig. 4.

EDXA spectrum for this new deposit is shown in Fig. 8a and a nearby reference surface spectrum is shown in Fig. 8b. It is not clear whether the original NaCl grain still underlies the new deposit. We know of no simple way that this composition could result from contamination, handling, or reaction with air or moisture; the best explanation seems to be that it represents a remobilization of the existing Zn (\pm Na) and S on the surface of the droplet.

In addition to loss of some of the phases, a softening and merging of some of the micromound textures appears to have occurred, and the surface now appears to be mottled at a coarser scale. It is possible that

some of these changes have resulted from reaction of the condensate phases with the moist Houston air. These samples were originally Au-Pd coated to a thickness of about 5 nm, and were stored in air in plastic boxes since their original studies. No attempt was made to keep them in a controlled atmosphere. It appears that at least some of the condensate phases are relatively unstable under terrestrial conditions. These observations emphasize the potentially fragile nature of the surface condensates and the necessity to protect the samples from atmospheric exposure. On the plus side, this instability may provide clues to the type of phases present.

Carbon on droplet surfaces. Analysis of surface grains and coatings of some droplets indicated the presence of carbon in some of the spectra (Fig. 7a). Because the grains were mounted on carbon planchettes, we originally attributed the carbon signal to stray X-rays from the planchette. However, closer examination and comparison with nearby broken or chipped surfaces under nearly identical geometric conditions showed that in most cases carbon was present on the original droplet surface but not on the nearby chipped surface (Fig. 7b). The chipping apparently occurred on the Moon, but the absence of micromound coatings on many chipped surfaces indicates that chipping probably occurred late in the eruption sequence or during the deposition of the pyroclastic deposit. We interpret this relationship to indicate that the carbon is a real component of the volatile coatings and condensed phases on the surface of the pyroclastic droplets.

It is possible that the driving gas for the pyroclastic eruption was CO. Some graphite remains in the sample, perhaps because of self-reduction displayed during intrinsic fugacity measurements. It is estimated that the orange glass reflects oxygen fugacity conditions about 0.5 to 1.0 log units above typical mare basalts and slightly above the iron-wustite buffer. Mao et al. [5] estimate on the basis of optical spectra that the orange glass was produced in a somewhat more oxidizing environment compared to typical lunar basalts. But Morris et al. [6] report some metallic iron present in all samples of orange and black glass, so the overall oxygen fugacity could not have been

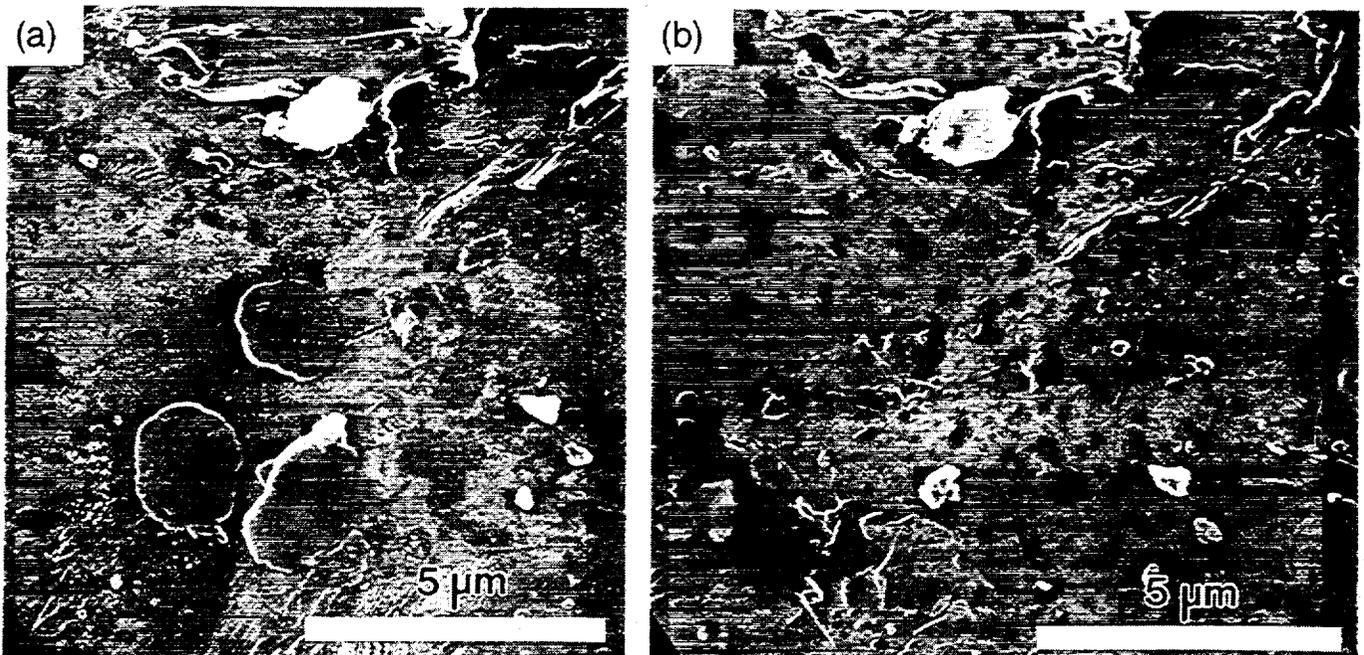


Fig. 5.

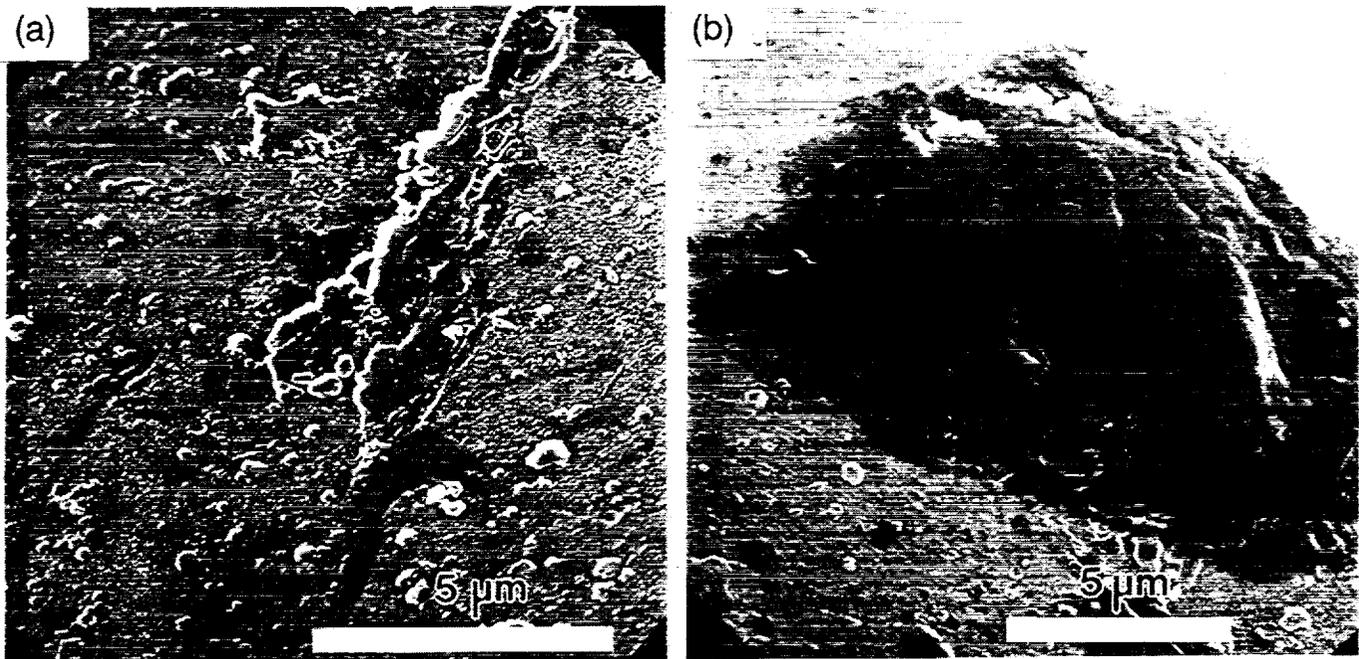


Fig. 6.

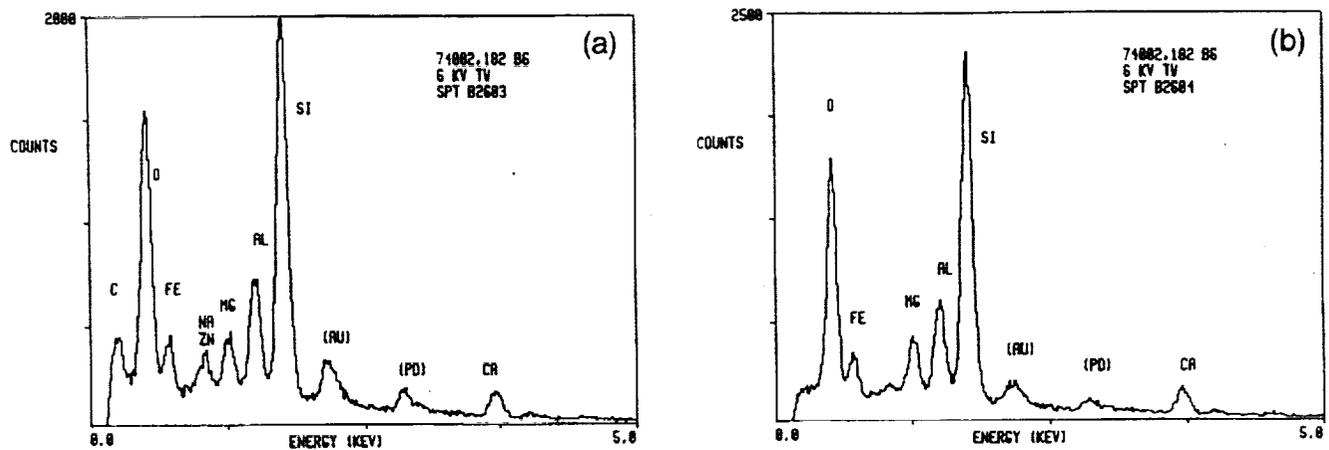


Fig. 7.

significantly above the iron-wustite buffer before and during the period when the glass was quenching. However, it may be that oxygen fugacity changed considerably during the eruption process. Normally CO gas would not leave a condensable trace. However, it is possible that during the rapid changes in pressure and temperature associated with the pyroclastic eruptions, a number of chemical reactions may have taken place that produced a condensable carbon phase. Because of rapidly changing conditions, these reactions would not necessarily reflect equilibrium conditions. An example might be a disproportionation reaction $\text{CO} \rightarrow \text{C} + \text{CO}_2$ that could have deposited carbon (graphite) on droplet surfaces during some phase of the eruption and cooling.

Another possibility is that a metal carbonyl was formed during some late stage of the eruption or after deposition and that this

carbonyl may have decomposed and deposited iron and some carbon on grain surfaces.

Yet another possibility is the formation of carbonates at lower temperatures, e.g., ZnCO_3 , during the late stages of the eruption or after deposition of the ejecta blanket. Such carbonates could form if CO_2 becomes a significant phase in the transient gas environment, produced, for example, by the disproportionation reaction described above. Although the orange and black glass is low in carbon [7], gas release studies indicated that CO_2 evolved at relatively low temperatures ($<400^\circ\text{C}$) and a carbonate phase might be present on grain surfaces.

Sulfur, sulfides, sulfates, or what? The association of sulfur with other volatiles such as Zn has been well documented for these surface coatings (e.g., [8]). Many have assumed the sulfur is present

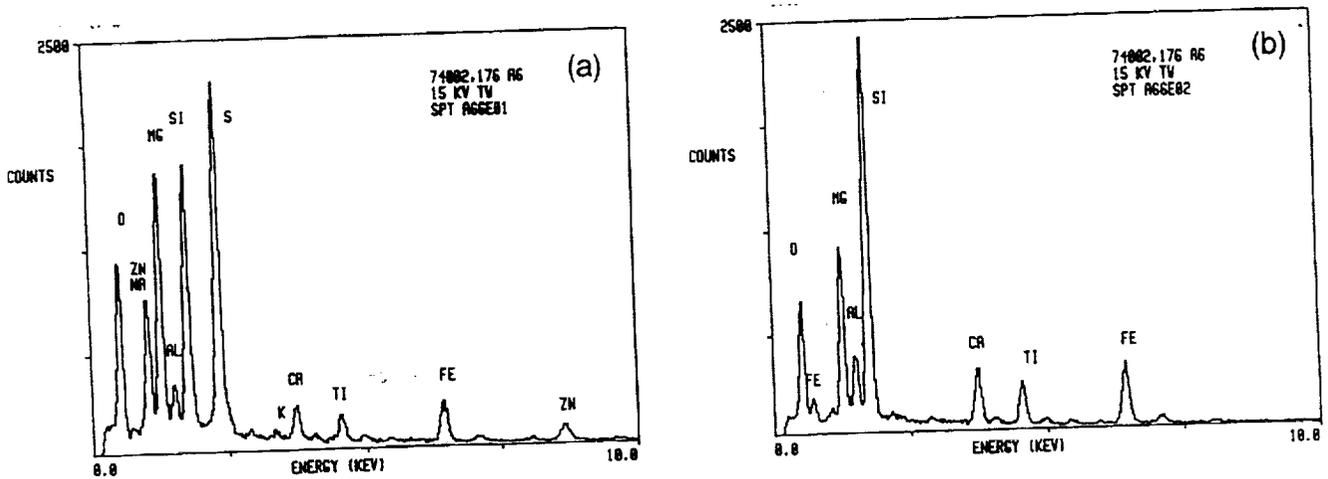


Fig. 8.

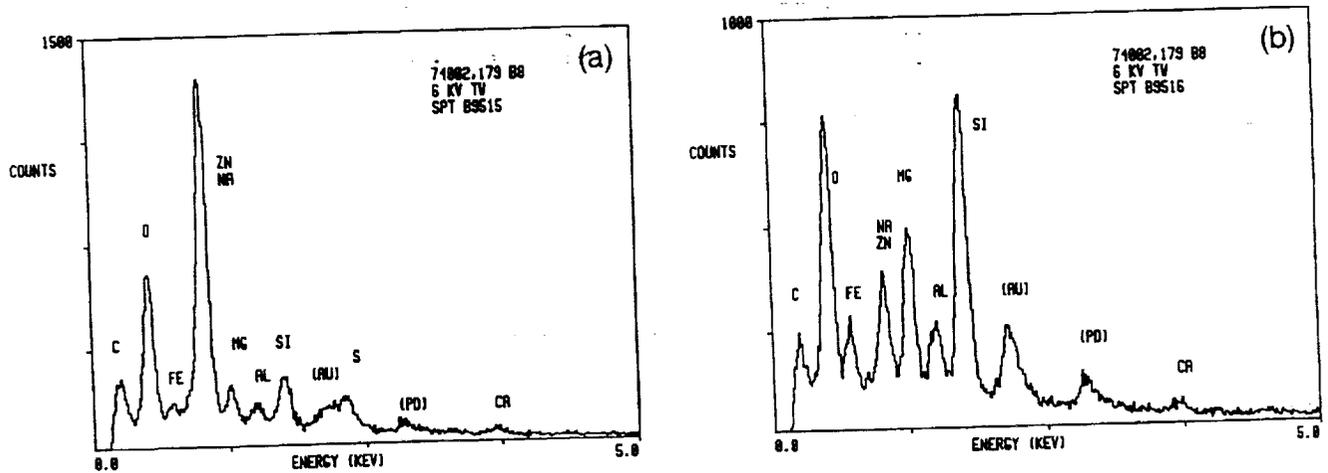


Fig. 9.

as a sulfide, but Clanton et al. [4] suggested that elemental sulfur might be present. Sulfur in combination with a variety of other species could also be present in amorphous vapor deposits. We have now observed two associations not previously reported that may bear on this question. First is the association of oxygen with sulfur when some small surface grains are analyzed. Second is the association, in some cases, of sulfur with both oxygen and carbon. Figure 9a illustrates the spectrum (6KV) from a small surface grain and Fig. 9b is from the adjacent "background" droplet surface. This pair illustrates that for the small grain, Zn (\pm Na), O, and C are all greatly enhanced with respect to major elements such as Si and Mg when compared to the background spectrum. Sulfur is a very minor peak on both spectra. While certainly not conclusive, this relationship suggests that the Zn may be present as an oxide or carbonate rather than a sulfide. Other examples of enhanced oxygen in specific condensate grains relative to the background silicate oxygen value are present. Both oxide and carbonate formation would probably require higher oxygen fugacities than necessary for sulfides or elemental sulfur, but, as discussed above, some increased oxygen fugacity compared to normal mare basalts may be indicated by other data, and late-stage increases in local oxygen fugacity during cooling or after deposition are also possible. However, we cannot rule out that the secular changes described above may have oxidized to some extent the original phases. Cirlin et al. [9] observed oxidized sulfur in XPS spectra of

74001, but proposed that the sulfates resulted from reactions with terrestrial air and water vapor. This can best be checked by analyzing for comparison freshly mounted pristine samples that have been maintained in nitrogen.

Summary and Conclusions: A review of existing data and new observations indicates that volatile condensates on Apollo 17 orange and black glasses are not only complex in chemistry but are complex in morphology and phase composition. New data indicate that carbon appears to be present in variable amounts on droplet surfaces. Zinc may be associated with oxygen and/or carbon in some cases, and a zinc carbonate or a zinc oxide appears to be a possible phase. Sulfates as a possible condensate are suggested by an apparent association of sulfur with oxygen, but verification will require more detailed work. Effects of exposure to air are clearly present and must be more fully analyzed before definitive condensate phase identification can be made. Additional studies of these phases may lead to a better understanding of the details of the eruption and could lead to better models of the gas phase composition and the fate of volatile species. Studies of lunar volcanic volatiles and condensates may also have major implications for lunar resource issues.

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Proc. LSC 4th, 397–412. [6] Morris R. et al. (1978) *Proc. LPSC 9th*, 2033–2048. [7] Gibson E. and Moore G. (1973) *EPSL*, 20, 404–408. [8] Butler P. and Meyer C. (1976) *Proc. LSC 7th*, 1561–1581. [9] Cirlin E. H. et al. (1978) *Proc. LPSC 9th*, 2049–2063.

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GEOLOGY OF THE APOLLO 17 SITE. W. R. Muehlberger,
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The Apollo 17 landing site was unique in several respects: (1) It was the only site that was not selected from telescopic-based geologic interpretation; interest in the site was generated by the visual observations of Al Worden, Apollo 15 Command Module pilot, who interpreted dark-haloed craters as possible cinder cones. (2) Instead of 20-m-resolution photographs, as was the norm for all earlier missions, this site had Apollo 15 panoramic camera photography coverage that had 2-m resolution. (3) It had a geologist-astronaut aboard who was intimately involved in all stages of planning and mission operation, and was also instrumental in the design of a long-handled sample bag holder that eliminated the need for the crew to dismount before collecting a sample, which then permitted sampling between major stations.

The following summary is mainly verbatim extracts (paragraphs) from reference [1], to which the interested reader is referred for details of site geology, sample description, and geologic synthesis of the site as viewed from studies through 1976.

The two major geologic objectives identified by the NASA Ad Hoc Site Evaluation Committee for this (the last) mission to the Moon were (1) sampling of very old lunar material such as might be found in pre-Imbrian highlands as distant as possible from the Imbrium Basin and (2) sampling of volcanic materials significantly younger than the mare basalts returned from the earlier missions. Photogeologic interpretation had suggested that such young volcanic materials on the Moon were pyroclastic, which would make them attractive not only for extending our knowledge of the Moon's thermal history, but because they might provide a record of volatile materials from the Moon's interior; furthermore, they might contain xenoliths of deep-seated lunar rocks.

Pre-mission Plans: The three traverses were designed to sample, observe, and photograph each of the units recognized in the landing area (listed in order of decreasing priority): highlands (massifs and

Sculptured Hills), dark mantle (interpreted to be young pyroclastic material), and subfloor material (interpreted to have been emplaced as a fluid, or fluidized, material).

Highland materials rim the Taurus-Littrow Valley and thus would be sampled at several stations along the base of the mountain fronts. In addition, large boulders that had rolled down the slopes would be sampled so that they could be restored to their initial position to determine whether there was any internal stratigraphy to the highlands (Serenitatis Basin or older basin ejecta beneath a cap of Imbrium ejecta). The light mantle at the base of the South Massif (an avalanche deposit believed to have been caused by ejecta from Tycho when it impacted the South Massif) was to be sampled at stations at various distances from the base of the massif in the hope that these would be samples representative of different stratigraphic (?) levels on the massif.

Dark mantle material, a veneer of dark material over both valley floor and highland regions, would be collected at several localities on the valley floor. The rims of large craters were places that it was hoped that the contact relations between the younger dark mantle and the older crater rim, wall, and floor materials could be observed. Ambiguous age relations where the boundary between the dark and light mantles appeared to be diffuse led to the possibility that they were, at least in part, deposited concurrently. Shorty and Van Serg Craters were planned for the study and collection of dark mantle material supposedly erupted from volcanic vents or excavated by impacts. Sampling of the dark mantle at different locations would provide information about lateral variation.

Large blocks on the rims of the large craters on the valley floor were interpreted to be subfloor material blasted to the rim by impact. Because Apollo 16 demonstrated that plainslike surfaces could be formed by impact ejecta, the nature and origin of the valley-filling material was in doubt, and awaited sampling to demonstrate that it was basalt as was the surface on which most other lunar landings had been made.

The Mission: The actual traverses closely approximated the planned ones. This was probably the result of fewer parts failures, better photography, which permitted better pre-mission interpretation/planning, and a timeline that had some flexibility. Emory Crater on EVA 1 was deleted, but Steno Crater, one of comparable size but closer to the LM, was sampled. Sherlock Crater, the last planned stop of EVA 3, was also deleted and only a scoop sample using the long-handled sampler was obtained about a crater radius from Sherlock.

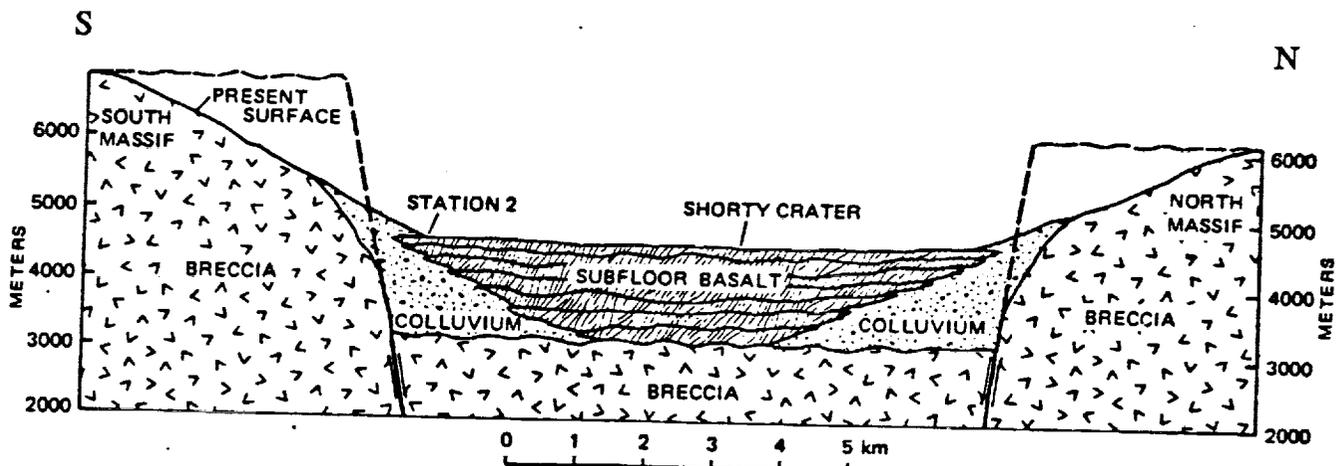


Fig. 1. Relations inferred among major subregolith units. Dark mantle is too thin to draw at this scale. Light mantle extends from the South Massif to just beyond Shorty Crater. No vertical exaggeration. Figure 242 in [1].